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PERFORMANCE-BASED PLASTIC DESIGN METHOD FOR BUCKLING-RESTRAINED BRACED FRAMES

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ABSTRACT

This paper presents the key design points of buckling-restrained braced frames (BRBFs) by using the performance-based plastic design (PBPD) methodology. This method is based on energy-work balance concept and uses pre-selected target drift and yield mechanism as design criteria. Based on multi-mode pushover and time-history analyses, a simple equation is developed for computing yield drift ratio, which is one of the essential parameters needs to be determined in the beginning of the design. The proposed equation accounts for higher mode effects as well as realistic boundary conditions of BRBs. In this study, two frames (one three-story and one six-story) were designed by PBPD method and their seismic performances were evaluated through nonlinear time-history analyses. It is shown that both frames showed intended yield mechanism and their drifts were well within the target drifts. The influence of P-Delta effect is also discussed.

Introduction

Buckling-restrained braced frames (BRBFs) are emerging systems used as primary lateral-load resisting systems for buildings in high seismic areas. This is primarily due to enhanced energy dissipation potential, excellent ductility, and symmetrical hysteretic response in tension and compression of the buckling-restrained braces (BRBs). Recent analytical and experimental studies have shown that BRBFs can be used to overcome several potential problems associated with conventional concentrically braced frames (Sabelli 2000, Fahnestock et al. 2007). Although BRBFs are expected to experience extensive inelastic deformations when subjected to severe ground motions, current design methods are still based on elastic analysis approach and use indirect ways to account for inelastic behavior. Trial-and-error is generally needed to achieve the desired response. In this study, a recently developed Performance-Based Plastic Design (PBPD) methodology was used to achieve the desired performance objectives of BRBFs in a direct manner. This design methodology has already been successfully applied to many steel framing systems (Lee and Goel 2001; Chao and Goel 2006; Chao and Goel 2008).

Performance-Based Plastic Design of BRBFs

PBPD concept uses pre-selected target drifts and yield mechanism as design criteria. In this method, the design base shear is computed using an energy-work balance concept where the

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energy needed to push an equivalent elastic-plastic single degree of freedom system up to the target drift level is calculated as a fraction of elastic input energy obtained from the selected elastic design spectra (Fig. 1). The resulting design base shear for a structure can be calculated by (Goel and Chao 2008):

$$V/W = \left(-\alpha + \sqrt{\alpha^2 + 4(\gamma/\eta)S_a^2}\right)/2 \tag{1}$$

where V is the design base shear; W is the total seismic weight of the structure; α is a dimensionless parameter, which depends on the natural period of the structure, the modal properties, and the intended plastic drift ratio (θ_p); S_a is the spectral response acceleration obtained from code design spectrum. The energy modification factor (γ) depends on the structural ductility factor (μ_s) and the ductility reduction factor (R_μ) and can be determined as follows:

$$\gamma = (2\mu_s - 1)/R_\mu^2 \tag{2}$$

The ductility reduction factor depends on the fundamental period and structural ductility factor of the structure. Thus, an inelastic spectrum, such as the one proposed by Newmark and Hall (1982), can be used to compute the value of R_μ. The energy reduction factor ($\eta = A_1/A_2$ shown in Fig. 2) accounts for the "pinched" hysteretic response of structural systems. Since the hysteretic responses of BRBFs are stable without any pinching, the value of η is used as unity in Eq. 1 for the computation of design base shear.

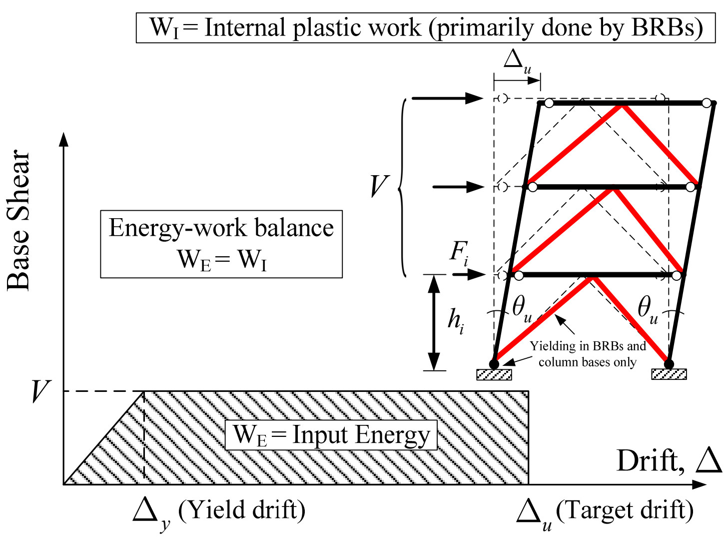


Figure 1. Energy-work balance concept.

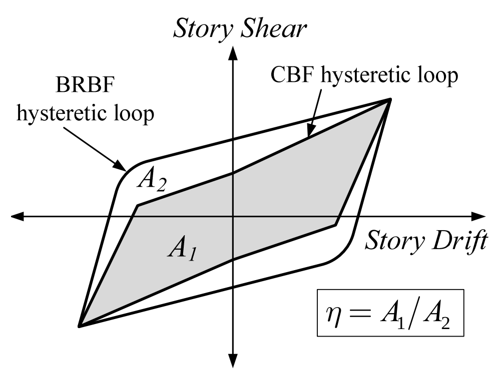


Figure 2. Energy reduction factor, η.

Step-by-step Design Procedure

1. Estimate the natural period (T) for the structure and select the intended target drift ratios for

expected hazard levels.

2. Compute the value of θ_p by deducting the yield drift ratio, θ_y, of the structure from the pre-selected target drift ratio, θ_u. Estimation of yield drifts for the BRBFs is discussed later.
3. Compute the value of α from the modal properties and plastic drift level using the equation proposed by Goel and Chao (2008).
4. Using Eq. 2, estimate the value of γ using the computed values of μ_s (i.e., the ratio of target drift ratio to yield drift ratio) and R_μ.
5. Compute the design base shear (V) for the structure using Eq. 1 and distribute the lateral load at various story levels based on a lateral load distribution that accounts for the inelastic behavior (Chao et al. 2007).
6. Determine the sizes of BRBs by resolving the computed story shear in the direction of braces for known value of yield strengths in tension and compression. It should be noted that the compressive yield strengths of BRBs are approximately 10% to 25% higher than the tensile strengths (Merritt et al. 2003).
7. Beams and columns (generally termed as non-yielding members) of BRBFs are then designed based on capacity design philosophy for the maximum demand expected from the BRBs at the ultimate state.

Determination of Yield Drift Ratios for BRBFs

As shown in the PBPD design procedure, yield drift ratio is an essential parameter that needs to be defined in the beginning of the design. The common way to evaluate the yield drift ratio of structure is to carry out conventional pushover analysis based on (a) code-specified lateral load distribution or (b) its fundamental mode shape. This procedure leads to reasonable values of yield drift ratio for low-rise structures; however, this may not be applicable to high-rise structures due to significant contribution of higher mode effects. When the conventional pushover analysis is performed, the effect of cumulative axial deformation of the columns results in significant lateral drifts (Taranath 2005). As a consequence, the first yielding in the structure occurs at a large drift ratio. However, especially for high-rise structures, the cumulative column axial deformation, thus the lateral drift, could be considerably reduced due to the higher mode effects (Fig. 3). As a result, the structural response obtained from the conventional pushover analysis generally overestimates the value of yield drift ratio.

Another important parameter affecting the yield drift ratio of BRBFs is the boundary conditions of braces. Prior studies (Lopez et al. 2002, Richard 2009) have shown that the yield drift ratio of a typical two-story BRBF is 0.17% rather than the theoretical value of 0.33% due to the shorter effective length of braces (approximately 60-70% of the working point length). As shown in Fig. 4, in general, the sizes of elastic and end zones are larger than that of restrained yielding segments. The length of elastic and end zones are nearly one-third of the total length. Thus, consideration of these realistic boundary conditions results in higher axial stiffness for BRBs, which in turn reduces the value of yield drift ratio for BRBFs.

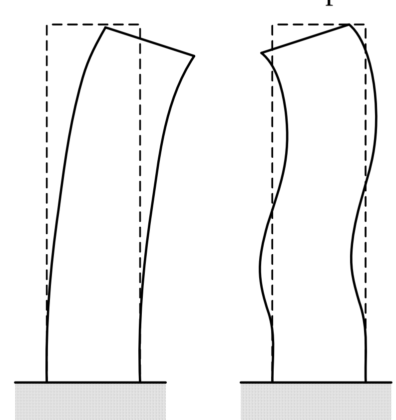
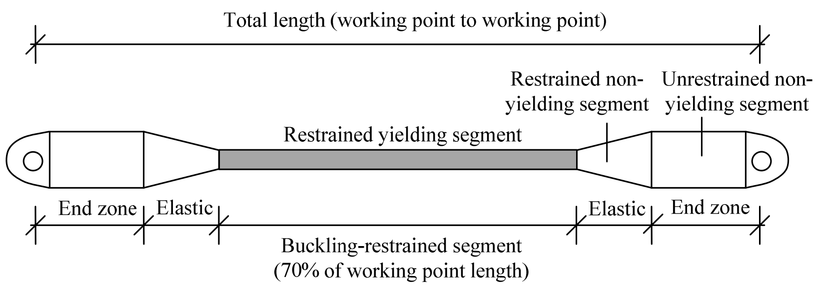


Figure 3. Deformation of structures at different vibration modes.



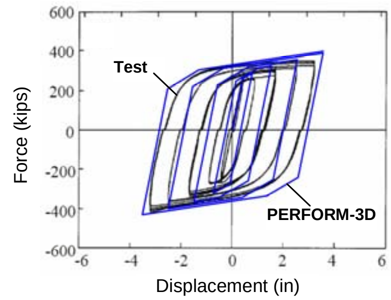


Figure 4. Actual boundary conditions of a typical BRB.

Figure 5. Hysteretic model.

Study Buildings

Four building (3-, 6-, 9-, and 18-story) were analyzed to investigate the yield drift ratios of BRBFs with different heights. All buildings were located on firm soil in central Los Angeles and considered in the SAC model-building analyses (MacRae 1999). The 3- and 6-story BRBFs were designed as per PBPD method discussed later, whereas the 9- and 18-story BRBFs were designed as per IBC (2006) equivalent lateral force procedure and AISC Seismic Provisions (2005). Further, BRBs in the 3- and 6-story BRBFs were arranged in chevron (inverted-V) pattern, whereas those in the 9- and 18-story BRBFs were arranged in cross (X-shape) pattern. The details of brace sizes as well as column and beam sections of the 9- and 18-story BRBFs can be found elsewhere (Richards 2009).

Computer Modeling

The nonlinear static and dynamic performance of BRBFs was evaluated by a nonlinear analysis program, PERFORM-3D (CSI 2007). Beams and columns were modeled as beam-column frame elements. For X-braced BRBFs (i.e., 9- and 18-story), beam-to-column connections were assumed as rigid where BRBs and gusset plates were present; otherwise these connections were assumed as pined. For 3- and 6-story BRBFs, moment release (Fig. 9) was used at the beam-to-column connections to eliminate the moment-frame action and prevent failure in the gusset regions (Fahnestock et al. 2007, Richard 2009, Thornton and Muir 2009). Consequently, the beam-to-column connections were modeled as pinned ones. For all cases, P-Delta effect due to gravity loads was included by adding gravity columns with hinged base and connected to the BRBFs through pin-ended rigid beams at each floor level. As shown in Fig. 4, the length of restrained yielding segment of a BRB was assumed as 70% of the total length. The effect of end conditions of BRBs was studied by considering two cases: (1) realistic boundary conditions, i.e., length of restrained yielding segment as 70% of total length (BRB 70), and (2) length of restrained yielding segment as 99% of total length (BRB 99, note that 100% of the working length is not allowed in PERFORM-3D). Further, the hysteretic response of BRBs was modeled by considering both the isotropic and kinematic hardening behavior. Various hardening parameters for the BRBs were obtained by calibrating the hysteretic models with the test results (Merritt et al. 2003) as shown in Fig. 5.

Nonlinear static (pushover) analysis was conducted for five cases of analyses having different combinations of mode shapes to evaluate the effect of higher modes on the yield drift ratio of BRBFs. These are: (a) Mode 1 (fundamental mode) only; (b) Combination of Mode 1 and Mode 2, both in the same direction (M1+M2); (c) Combination of Mode 1, Mode 2, and Mode 3; all in the same direction (M1+M2+M3); (d) Combination of Mode 1 and Mode 2, acting in opposite directions (M1-M2); and (e) Code-based lateral load distributions. For combination cases (b), (c), and (d), the base shear values were multiplied by scale factors (CSI 2007) equal to the values of spectral acceleration at the respective periods of the BRBFs obtained from the response spectra as per ASCE 7 (2005), as shown in Fig. 6. Nonlinear time-history analysis was carried out using twenty ground motions representing life-safety (10% in 50 years) hazard level (Somerville et al. 1997).

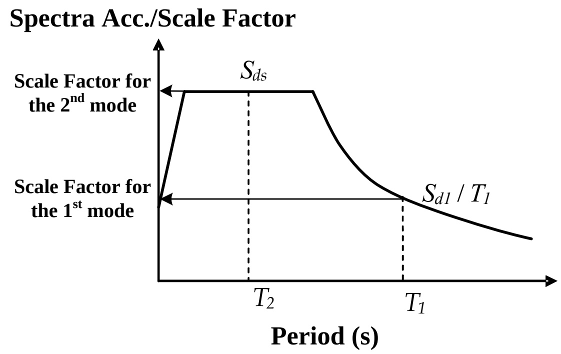


Figure 6. Computation of scale factor from design response spectra.

Results

The first phase of nonlinear static analysis was carried out to investigate the effects of brace boundary conditions. Therefore, only the code-specified lateral load distribution was used in the analysis. Fig. 7 compares the yield drift ratio (YD) for BRBFs with BRBs having different boundary conditions. Note that YD in this paper is defined as the point when the base shear versus drift ratio curve starts deviating from the elastic response. YD is generally slightly larger if it is defined as the intersection of the elastic and post–elastic curves. As expected, BRBFs with length of the restrained yielding segment as 99% of the working point length showed smaller lateral stiffness and larger values of yield drift ratios. The values of yield drift ratio for 3-, 6-, and 9-story BRBFs were about 0.4%, whereas the yield drift ratio of the 18-story BRBF was about 0.9%. Table 1 compares the values of roof drift ratio and story drift ratio at the first yielding of both the 3- and 6-story BRBFs. As can be seen for both BRBFs, smaller roof and story drift ratios were noticed for BRB 70 case as compared to the BRB 99 case. The values of yield drift ratio for 3-, 6-, 9-, and 18-story BRBFs with BRB 70 were found to be 0.34%, 0.37%, 0.38%, and 0.78%, respectively.

Table 1. Drift levels at first yielding of braces of the 3- and 6-story BRBFs.

Story level with first yielding	**3-story BRBF**				**6-Story BRBF**			
	BRB 70		**BRB 99**		**BRB 70**		**BRB 99**	
	Roof drift ratio	Story drift ratio	Roof drift ratio	Story drift ratio	Roof drift ratio	Story drift ratio	Roof drift ratio	Story drift ratio
1st	0.0042	0.0042	0.0047	0.0047	0.0041	**0.0033**	0.0046	**0.0037**
2nd	**0.0034**	**0.0036**	**0.0038**	**0.0042**	**0.0037**	0.0044	**0.0042**	0.0049
3rd	0.0042	0.0038	0.0047	0.0042	0.0041	0.0047	0.0046	0.0052
4th	-	-	-	-	0.0041	0.0044	0.0046	0.0050
5th	-	-	-	-	0.0050	0.0046	0.0051	0.0048
6th	-	-	-	-	0.0045	0.0044	0.0051	0.0050

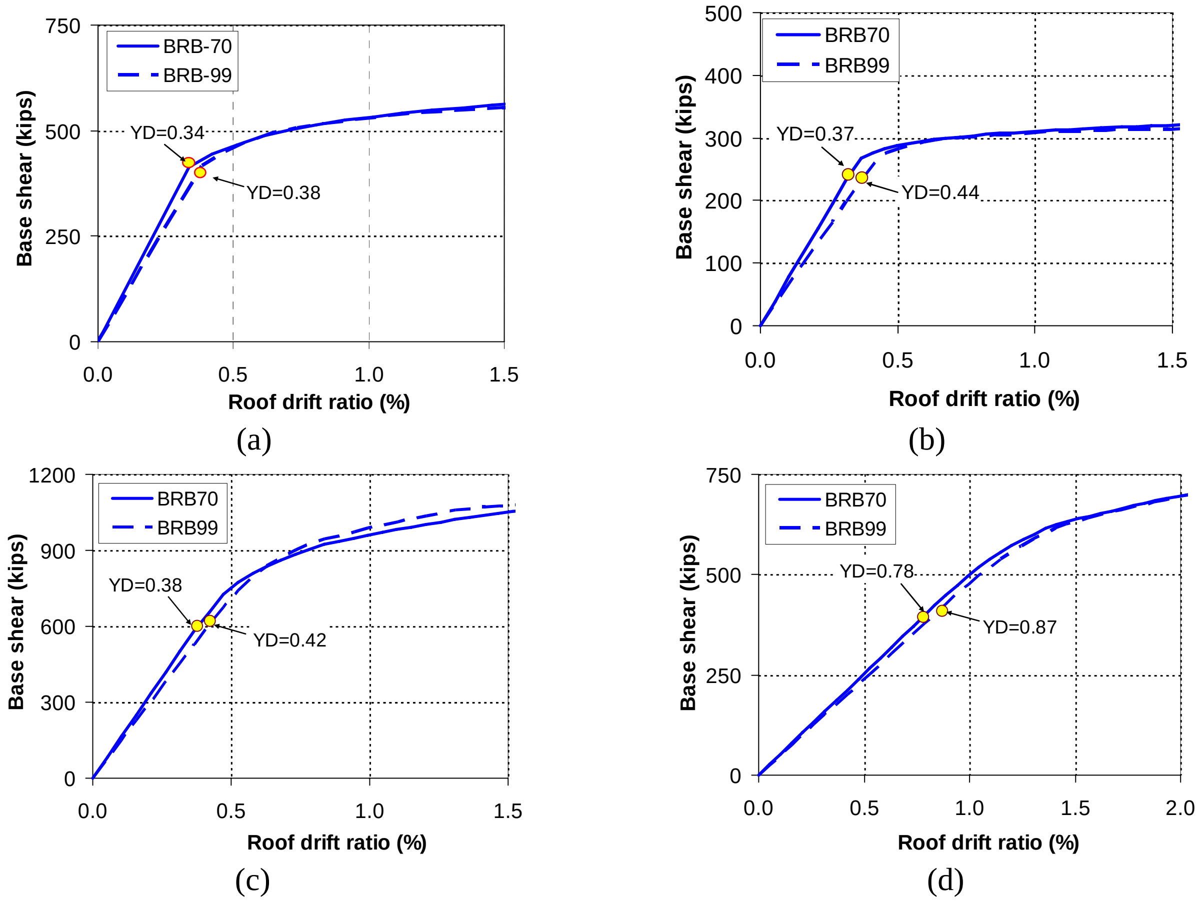


Figure 7. Yield drift ratios of BRBFs with different boundary conditions of BRBs (a) 3-story (b) 6-story (c) 9-story (d) 18-story.

Since the higher mode effects are not so critical for the low-rise structures, the pushover analyses for higher mode cases were only carried out for the 6-, 9-, and 18-story BRBFs (BRB 70 only). Two vibration modes were considered for 6-story BRBF, whereas three consecutive vibration modes were considered for both the 9- and 18-story BRBFs. As shown in Figs. 8(a), (b), and (c), the positive combinations of modes (e.g., M1+M2, M1+M2+M3, etc.) resulted in higher base shear, whereas the opposite combinations (e.g., M1-M2) yielded smaller value of base shear. However, it is interesting to note that the values of yield drift ratios are very close, irrespective of the modal combinations. The capacity curves for all BRBFs were nearly the same for the pushover analysis cases using the code-specified lateral force distribution and the first mode shape. The effects of higher modes on the yield drift ratio can be clearly observed: YD is generally much smaller when multi-modes are considered, especially for the 18-story BRBFs.

The mean values of yield drift ratios obtained from twenty time-history analyses (THA shown in Fig. 8) were close to those obtained from the multi-mode pushover analyses. The pushover analysis using either code-specified lateral load distribution or first mode shape resulted in somewhat upper-bound yield drift ratios for all BRBFs. By using the maximum yield drift ratios obtained from all time-history analyses, a regression analysis was carried out to establish a simple and slightly conservative relationship between the yield drift ratio and the height of BRBFs. As shown in Fig. 8(d), yield drift ratio of BRBFs can be expressed as follows:

$$YD = 0.2 + H/500 \quad (3)$$

where YD = yield drift ratio in percentage, H = total height of BRBF in ft.

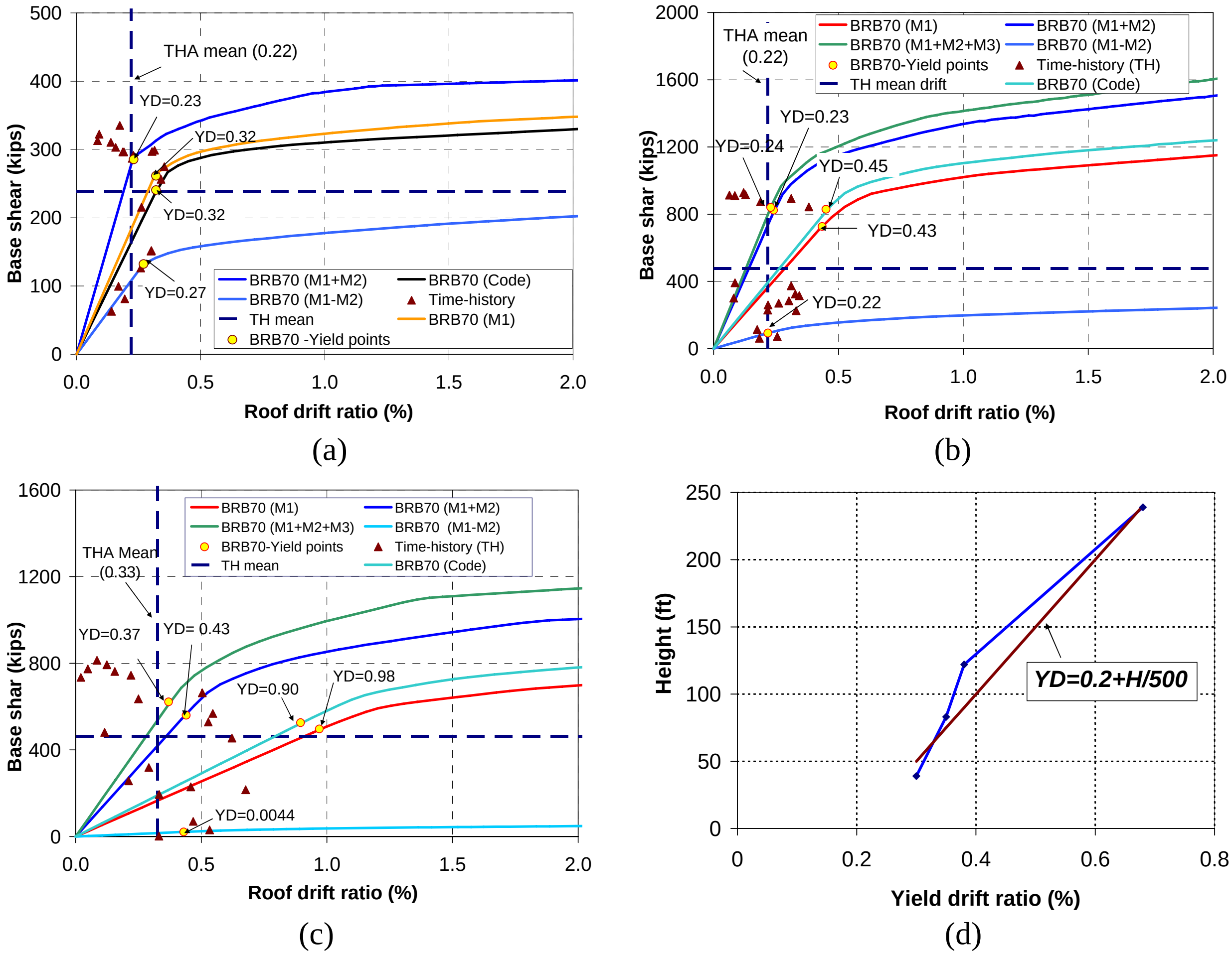


Figure 8. Comparison of yield drifts obtained from time-history analysis and pushover analysis (a) 6-story (b) 9-story (c) 18-story (d) Relationship between yield drift and height.

Evaluation of Seismic Performance of BRBFs Designed by the PBPD Approach

Two BRBFs (3- and 6-story) were redesigned as per PBPD methodology and Eq. 3. The target drift ratio θ_u for both BRBFs was selected as 1.75% for the 10% exceedence in 50 years hazard level. Table 2 summarizes the corresponding parameters used for computing the design base shears for the 3- and 6-story PBPD BRBFs. A strength reduction factor of $\phi = 0.9$ was used for the design of brace sections (in both tension and compression). For the determination of BRB sizes and strengths, the values of compression strength adjustment factor and tension strength adjustment factors were considered as 1.1 and 1.4, respectively. The BRBs were assumed to have been made of steel plates with a nominal yield strength 36 ksi and material overstrength factor of 1.3 (AISC 2005). Fig. 9 shows the expected yield strength of braces and sections used for beams and columns in both BRBFs. As stated earlier, both BRBFs were modeled by PERFORM-3D (CSI 2007) and their seismic performance was evaluated under twenty SAC 10%

exceedence in 50 years hazard level ground motions. For each case, Rayleigh damping coefficient was assumed as 2% of critical value in the time-history analysis. For all cases, bases of columns were assumed to be perfectly fixed to the ground.

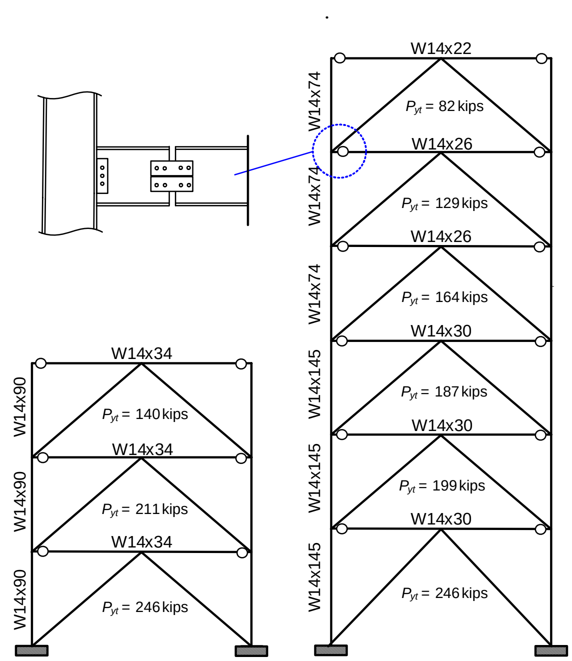
Table 2. PBPD Design Parameters for the 3-story and 6-story BRBFs.

Sl. No.	Parameters	3-story	6-story	Note
1	Target drift ratio θ_u (%)	1.75	1.75	Pre-selected
2	Height (ft)	39	83	Ref.: Sabelli (2000)
3	Yield drift ratio θ_y (%)	0.28	0.37	Eq. 3
4	Natural period (sec.)	0.43*	0.77**	Ref.: ASCE 7-05 (2005), C_u = 1.4
5	Inelastic drift ratio, $\theta_p = \theta_u - \theta_y$ (%)	1.47	1.38	(5) = (1) – (3)
6	Ductility reduction factor, R_μ	4.79	4.78	Ref.: Chao and Goel (2008)
7	Structural ductility factor, μ	6.25	4.78	(7) = (1)/(3)
8	Energy modification factor, γ	0.505	0.375	Eq. 2
9	Spectral acceleration, $S_a = C_s R/I$	1.392	1.00	Response reduction factor, R=8; Importance factor, I =1; Base shear coefficient, C_s = 0.174
10	Base shear ratio, V/W	0.158	0.10	V = 257 kips (3-story); 221 kips (6-story)

* 0.65 sec. based on computer analysis; **1.03 sec. based on computer analysis

The main parameters of BRBFs investigated in the present study were the interstory drift ratios, the overall yield mechanism, and the influence of P-Delta effect. It is noted that, due to the well-controlled drift (1.75%) defined in the beginning of the PBPD approach, no additional design force was used in the design to account for the P-Delta effect. A statistical analysis was carried out to evaluate the mean and standard deviation of drift ratios for both BRBFs. The effect of P-Delta on the seismic response of BRBFs was evaluated by including and excluding the gravity columns in the analytical models.

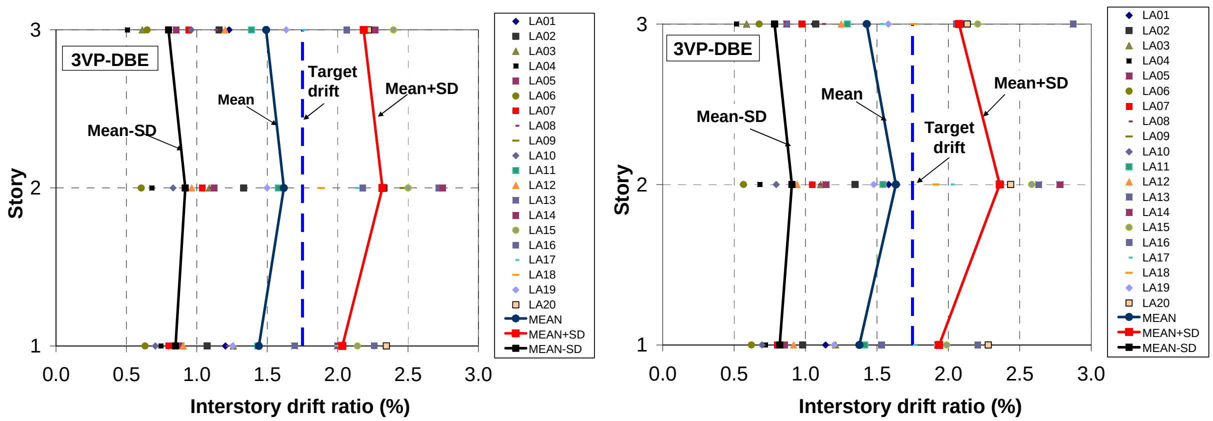
While the yielding at the column bases and in the BRBs of 3-story BRBF was noticed, no plastic hinges occurred in beams and other columns for all the ground motions. Therefore the intended yield mechanism was achieved. Mean values of the maximum interstory drift ratios for the 3-story BRBF were 1.62% and 1.63%, for with and without P-Delta cases, respectively (Fig. 10). This indicates that the drift-control incorporated in the PBPD design base shear allows no supplementary design force being considered to account for the P-Delta effect. Also, mean value of the maximum interstory drift ratios for 3-story BRBF was very close to the pre-selected target drift level of 1.75%. Similar to 3-story BRBF, the 6-story BRBFs did not show plastic hinges in beams and columns for both P-Delta cases. Mean



(a) (b)

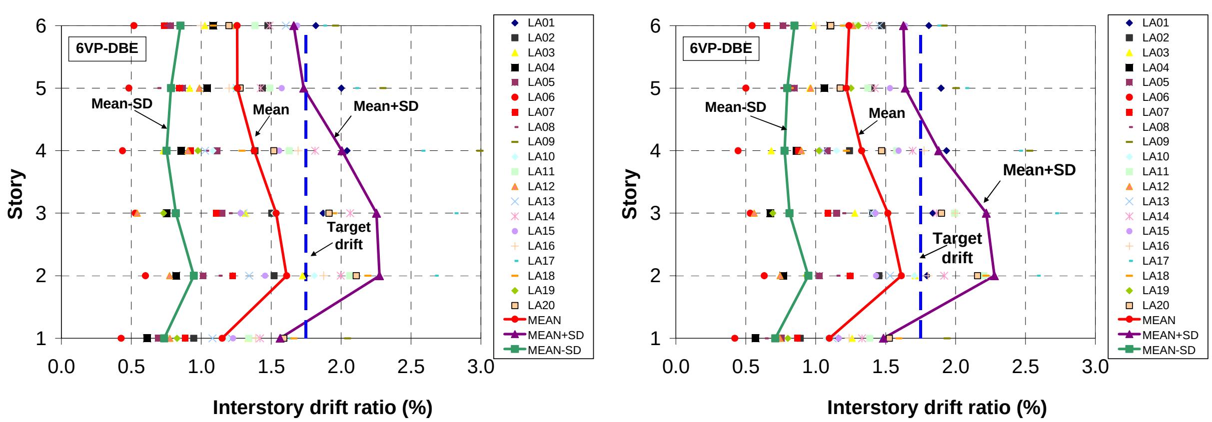
Figure 9. Details of BRBFs designed by PBPD method: (a) 3-story (b) 6-story.

value of the maximum interstory drift ratios for both cases of 6-story BRBF was 1.61% (Fig. 11), indicating the negligible effect of P-Delta effect on the maximum interstory drift response. Thus, both 3-story and 6-story BRBFs were within their target drift levels and achieved desired yield mechanisms for life safety hazard level. It should be noted that no iteration for design was carried out in the PBPD method to achieve the desire target drift levels, because inelastic behavior of the structures was considered directly in the design.



(a) (b)

Figure 10. Comparison of interstory drift for 3-story BRBF (a) with P-Delta; (b) without P-Delta.



(a) (b)

Figure 11. Comparison of interstory drift for 6-story BRBF (a) with P-Delta; (b) without P-Delta.

Conclusions

1. Based on multi-mode pushover and time-history analyses, a simple equation is developed for computing yield drift ratio for BRBFs. The proposed equation accounts for higher mode effects and realistic boundary conditions of BRBs, thus it is applicable to typical low- to high-rise BRBFs.
2. BRBFs designed as per performance-based plastic design (PBPD) methodology can successfully limit the maximum drifts within the pre-selected target drift level, as well as achieve the intended yield mechanism for the life safety hazard level.
3. The P-Delta effect resulting from gravity loads on the seismic performance is fairly small

for the study 3- and 6-story BRBFs, primarily due to the well-controlled drifts. Thus, the inclusion of additional P-Delta shear in the calculation of design base shear can be neglected.

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